Spintronics - A Vision for Future in Electronics and Computers

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Abstract: Conventional electronic devices based on the transport of electrical charge carriers - electrons - in a semiconductor such as silicon. Spintronics is an emerging field of electronics, where instead of using the charge of electrons, devices work by manipulating electron spin. In this paper, a new paradigm of electronics based on the spin degree of freedom of the electron. Either adding the spin degree of freedom to conventional electronic devices or using the spin alone has the potential advantages of non-volatility, increased fast speed of data processing, decreased electric power consumption, more versatile and increased integration densities compared with conventional semiconductor devices. Spintronics is an emerging field of electronics, trying to use in digital electronics and it promises to build faster and more efficient computers and applications. Spintronics is an exciting field that holds promise to build faster and more efficient computers and devices.

Keywords: Spintronic devices, spin transport, optical spin manipulation, and efficient injection, spin polarization and spin polarized currents.

I. INTRODUCTION

Spintronics is a branch of physics concerned with the storage and transfer of information by means of electron pairs in addition to electron charge as in conventional electronics. Spintronics is made up of two words “spin transport and electronics”. It is also known as fluxtronics, an emerging technology of nanoscale electronics involving the detection and manipulation of electron spin. It is new science of electronics and computing field. Spintronics exploits another fundamental property of that electron, called “spin”. “Spin” refers to intrinsic angular momentum of the electron, and makes it behave as a tiny magnet. Electron spin can be detected as a magnetic field having two possible states known as down and up. This provides an additional two binary states to the conventional low and high logic values, which are represented by simple currents. It played an important role not only in solid state physics, and possible devices that specifically exploit spin properties instead of or in addition to charge degrees of freedom but also for ready demonstrated potential these phenomena have in electronic technology.

The prototype device that is already used in industry as a read head and a memory storage cell is the “Giant magnetoresistance” (GMR) which consists of alternating non-magnetic and ferromagnetic layers. Recent efforts in GMR technology have also involved magnetic tunnel junction devices where in tunneling current depends on spin orientations of the electrodes. With the addition of spin state to the mix, a bit can have four possible states, which might be called down-low, down-high, up-low, and up-high. These four states represent quantum bits (qubits) potentially, this technique could then be used to transmit or store data on an unprecedented scale.

The discovery of these spin dependent effects in metallic electrical transport has spawned a wide range of further investigations and has united previously distinct subfields of physics into the new field of Spintronics. This includes spin dependent transport in semiconductors, spin-dependent tunneling through insulators, and spin transport effects driven by the spin-orbit interaction in semiconductors, oxides, and metals. Some of the themes of Spintronics will be explored in sections II and III including concepts of spin transport, its characteristics, its applications and spin-dependent electrical properties of materials. Spintronic technology has been tested in mass storage components such as hard drives. The technology tried to use in digital electronics and it promises the potential create a new generation of super-fast computers, capable of processing vast amounts of data in energy-efficient way. The existence of four, rather than two, defined states for a logic bit translate into higher data transfer speed, greater processing power, increased memory density, and increased storage capacity, provided the properties of electron spin can be sufficiently controlled by practical applications. Spintronics is an exciting field that holds promise to build faster and more efficient computers and devices.

II. CONCEPTS OF SPINTRONICS

Spintronics emerged from discoveries in the 1980s concerning spin-dependent electron transport phenomena in solid-state devices. This includes the observation of spin-polarized electron injection from a ferromagnetic metal to a normal metal by Johnson and Silsbee (1985), and the discovery of giant magnetoresistance independently by Albert Fert et al. and Peter Grünberg et al. (1980)[1].
intriguing devices for more efficient information processing have emerged in the first decade of the new millennium. A new area is discussed in electronics, an area that has seen various degrees of experimental success in proving that information can indeed be encoded, transported and stored using both electron charge and spin. Spin allows for the differentiation between electrons grouping them into two types, “spin-up” and “spin-down” depending on their +1/2 and -1/2 spin projection onto a given quantization axis. In ferromagnetic materials, there is an imbalance at the Fermi level in the number of “spin up” and “spin down” electrons. Because of imbalance, electrons travelling from one metal ferromagnet to another through a non-magnetic spacer carry an information about the magnetization of the first ferromagnet. The spin of a single electron is considered a suitable entity to encode a qubit.

Fig.-1 Spin resolved density of the states in neutral and ferromagnetic metals.

A coherent superposition of “spin up” and “spin down” states. Thus, information can be encode via electron spin and transported from one part of the device to another using electron current, if certain conditions are met for the phase coherence to be maintained. The coding can be changed by remagnetizing the metal ferromagnet containing the information. Generation and control of spin polarized electrical conduction while maintaining phase coherence is likely to have great impact on quantum information technology. A net spin polarisation can be achieved either through creating an equilibrium energy splitting between spin up and spin down such as putting a material in a large magnetic field (Zeeman Effect) or the exchange energy present in a ferromagnet or forcing the system out of equilibrium. Spintronics is based on three factors: spin injection, spin transport, and spin selective detection.

(A). SPIN INJECTION AND SPIN TRANSPORT

According to Mott’s model, “spin-up” and “spin-down” electrons exist in two different channels in a ferromagnetic material. Although spin-flip scattering occurs between the two channels resulting in spins losing their initial orientation, it is often neglected given the short time scales of all other processes in the system. Nonetheless, the density of states in the two spin channels is different and the electrical current is primarily due to electrons with a lower density of states at the Fermi level. These are known as “minority spin carriers”, opposed to “majority spin carriers” corresponding to those with a higher density of states. It is useful to define two quantities (a) density of states (DOS) spin polarisation $p(\text{dos})$ of the injector ferromagnet and (b) spin polarisation $\eta$ of the injected current (also known as spin injection efficiency).

Minority spins constitute a good supply of spins when the current passes from a ferromagnet to a non-magnetic material. Spin injection is achieved by using ferromagnetic contacts, commonly described as “spin injectors”. In electrical spin injection a magnetic electrode is connected to the sample. When the current drives spin polarised electrons from the electrode to the sample, non-equilibrium spin accumulates there. Many materials in their ferromagnetic state can have a substantial degree of equilibrium carrier spin polarization. Non-equilibrium spin is the result of some sources of pumping arising from transport, optical, or resonance methods. Once the pumping is turned off the spin will return to its equilibrium value. Electrical spin injection is an example of transport method for generating non-equilibrium spin, has already been realised experimentally by Clark and Feher who drove a direct current through a sample of InSb in the presence of constant applied magnetic field. Generation of non-equilibrium polarisation and spin accumulation is also possible by optical methods known as optical orientation or optical pumping. In optical orientation, the angular momentum of absorbed circularly polarised light is transferred to the medium. Transport, optical and resonance methods have all been used to create nonequilibrium spin. For most cases of simple macroscopic-charge-current-flow, such as current flow in metals, transport is analysed assuming that the charge carriers are in a local equilibrium. Spin transport requires a new descriptive framework. The spin of an electron can be altered through interaction with the external fields or the surroundings and, hence, is not a conserved quantity for carriers. For “spin transport”, however, the basic principle is to create a (nonequilibrium) population of carriers inside the device such that the net spin moment is non-zero and to manipulate this spin polarisation via a gate electrode or some local magnetic field for device operation. The theoretical treatment can also be simplified considerably if a single quantisation axis can be selected and the spin polarisation in transverse directions can be neglected. In this situation, referred to as incoherent spin transport, a quasi-chemical potential can be introduced for each of the two spin directions of a spin-1/2 particle, a spin-up quasi-chemical potential, and a spin-down quasi-chemical potential. “Quasi-chemical potential” refers to a model where the spin-up carriers are considered to be a local equilibrium with other spin up carriers but spin-up and spin-down are not in an equilibrium to each other. This is very similar model to that used to describe non-equilibrium transport in semiconductors. If a single quantisation axis cannot be defined, then the system is in the realm of coherent spin transport. One approach to the theory of coherent spin transport is to consider the evolution of the spin density matrix through the system instead of merely considering the evolution of diagonal elements.

(B). SPIN DETECTION

The most obvious approach to the electrical detection of spin populations in semiconductors and other devices is to use spin dependent transport properties of semiconductor-ferromagnetic interfaces. Spin valve detection scheme have used ohmic contacts for the spin collection electrode. But there is difficulty arises that it appears that for effective spin collection, either a ballistic contact or a tunneling contact...
from the semiconductor to a ferromagnet will be required. An alternative spin detection scheme is a potentiometric measurement, with a ferromagnetic electrode, of the chemical potential of the non-equilibrium spin populations.

III. SPINTRONICS DEVICES

In the last decade there were significant advances in the field of Spintronics. New effects, new functions and new devices have been explored. The spin polarised current was efficiently injected from a ferromagnetic metal into a non-magnetic metal and a semiconductor, the method of electrical detection of spin current was developed. However, the efficiency of Spintronics devices is still low. At present, most Spintronics devices either operate at cryogenic temperatures or have a spin-dependent output signal, which is just a little above noise level. It is important to improve the performance of Spintronics devices otherwise they have no chance of competing with Si-electronics devices [2]. There are many advantages of spin-related effects is that they have significant magnitude. Ferromagnetic metals own their great carrier as Spintronics materials to the spin effects they display. The most practical application are giant magnetoresistance and tunneling magnetoresistance in devices built for ferromagnetic metals. The discovery in 1988 of the GMR is considered the beginning of the new, spin based electronics. It is observed in artificial thin-film materials composed of alternate ferromagnetic and non-magnetic layers. Resistance of metals depends on the mean free path of the conduction electrons- shorter the mean free path higher the resistance. The resistance of material is lowest when the magnetic moments in ferromagnetic layers are aligned and highest when they are anti-aligned. The current can either be perpendicular to interfaces (CPP) or can be parallel to interfaces (CIP). An external magnetic field, below a certain magnitude, can change the magnetisation direction of the free ferromagnet without altering the direction of magnetisation of the pinned ferromagnet, this leads to phenomenon of GMR. Another important phenomenon is tunneling magnetoresistance (TMR) and magnetic tunnel junctions with ferromagnetic electrodes. The resistance of MTJ is different for the parallel and antiparallel magnetic configurations of their electrodes. Some early observations of TMR effects, small and at low temperatures, had been already reported by Julliere. The MTJ are at the basis of new TMR effects, small and at low temperatures, had been already reported by Julliere. The MTJ are at the basis of new configurations of their electrodes. Some early observations of TMR effects, small and at low temperatures, had been already reported by Julliere. The MTJ are at the basis of new configurations of their electrodes. Some early observations of TMR effects, small and at low temperatures, had been already reported by Julliere.

IV. SPINTRONICS WITH SEMICONDUCTORS

It is very attractive as it can combine the potential of semiconductors (control of current by gate, coupling with optics) with the potentials of magnetic materials. For example- to gather storage, detection, logic, and communication capabilities on a single chip that could replace several components. New concept of components have also been proposed, for example, the concept of spin field effect transistor (Spin FETs) based on spin transport in semiconductor lateral channels between spin polarised source and drain with control of spin transmission by a field effect gate . Some nonmagnetic semiconductors have a definite advantage on metal in terms of coherence time and propagation of spin polarisation on long distances. Spintronics with semiconductors is currently developed along several roads.

a. Another way for Spintronics with semiconductors is based on the fabrication of ferromagnetic semiconductors. Schmidt have raised the problem of “conductivity mismatch” to inject a spin-polarized current from a magnetic metal into a semiconductor. Solutions have been proposed by the theory19-20 and one knows today that the injection/extraction of a spin-polarized current into/from a semiconductor can be achieved with a spin-dependent interface resistance, typically a tunnel junction. Spin injection/extraction through a tunnel contact has been now demonstrated in spin LEDs and magneto-optical experiments. However, in structures for lateral spin transport between spin-polarized sources and drains, only very modest results have been obtained up to now, contrast between parallel and antiparallel magnetic configurations of the source and the drain never exceeding a few %.
temperature ferromagnetic semiconductors have been announced but the situation is not clear on this front yet. ii) The research is now very active on a third way exploiting spin-polarized currents induced by spin-orbit effects, namely the Spin Hall, Rashba or Dresselhaus effects. In the Spin Hall Effect\textsuperscript{21}, for example, spin-orbit interactions deflect the currents of the spin up and spin down channels in opposite transverse directions, thus inducing a transverse spin current, even in a nonmagnetic conductor. This could be used to create spin currents in structures composed of only nonmagnetic conductors [3].

V. OPTICAL MANIPULATION OF SPIN
The photon itself couples only weakly to spin, however the spin orbit interaction permits spin-selective optical transitions to occur even through electric dipole interactions. The details of such transitions depends on the electronic structure of the specific material, and most optical experiments to probe the dynamics have been performed on direct gap zincblende semiconductors. For these materials, the conduction band has s-like symmetry and valence band has p-like symmetry. The crystal field of the semiconductor does not further split the electronic states in the conduction or valence band at point. Instead, of splitting that occurs due to spin-orbit interaction, which splits the six p states into a four fold degenerate $j=3/2$ multiplet and $j=1/2$ doublet. The valence-band edge corresponds to $j=3/2$ multiplet, and the individual states are labelled by heavy hole and light hole up and down. The heavy hole corresponds to orbital angular momentum parallel to spin angular momentum and are product states of spin and orbit. An electric dipole transition will be a spin-conserving transition and, if it involves circularly polarised light, will either change the orbital angular momentum by $+1(\sigma_+) = \text{heavy hole} = +1/2$ or $-1(\sigma_-)$ along the axis of propagation. The probability of first process is three times larger than the probability of second. Thus circularly polarised light will generate an optically excited density of spin polarised conduction electrons, with a maximum polarisation 50%

$$P \text{ density } = n \uparrow n \downarrow / n \uparrow n \downarrow$$

Time resolved non-linear optical techniques have provided direct measurements of the evolution of the population of spins, once they have been injected into a nonmagnetic semiconductor. optical pulses are used to create a superposition of the basis spin states defined by an applied magnetic field and follow the phase, amplitude, and location of the resulting electronic spin precession(coherence) in bulk semiconductors, heterostructures, and quantum dots, nanosecond dynamics persist to room temperature, providing pathways toward practical coherent quantum magneto electronics.

VI. APPLICATION OF SPINTRONICS

1. Magnetic Random Access Memory (MRAM) - a new type of non-volatile memory that uses magnetic moments to retain data instead of electrical charges. Advantages are lower cost, smaller size, faster speed and less power consumption. These can survive even in high temperature and high level radiations or interference.

2. Giant Magneto Resistance (GMR) - GMR can be considered the first real applications of the promising field of nanotechnology. GMR refers to a large change in resistance (typically 10 to 20%) when the devices are subjected to a magnetic field, compared with a maximum sensitivity of a few percent for other types of magnetic sensors. It is used to make more sensitive hard disk drives read heads.

3. GMR Sensors
GMR sensors are already being developed in UK universities. They have a wide range of applications and the market is worth 8 billion dollars a year. GMR sensors are used for a wide range of applications.
1. Fast and accurate position and motion sensing of mechanical components in precision engineering and robotics.
2. All kinds of automotive sensors for fuel handling systems, anti-skid systems, speed control and navigation, Missile guidance.
3. Position and motion sensing in computer video games

4. SPIN Valves
Spin valves are not only highly sensitive magnetic sensors but these can also be made to act as switches by flipping magnetization in one of the layers parallel or anti parallel as in a conventional transistor memory device.

5. Creating Faster Computers
Silicon is widely used in electronics industry. So, hybrid devices that combine magnetic layers with semiconductors like silicon could be made to behave more like conventional transistors. These could be used as non-volatile logic elements that could be reprogrammed using software during actual processing to create an entirely new type of very fast computers.

6. Quantum Computers
one of most ambitions devices is the spin based quantum based computer in solid state structures using electron spin.
for this purposes is an obvious idea since fermions with $\frac{1}{2}$ spin is a natural and intrinsic qubit. The applications of Spintronics in quantum computation has focused on using quantum-dot-trapped electron spins in GaAs. Because of the three dimensional confinement and the fact that GaAs conduction band is mainly band in mainly formed from $'s'$ atomic orbital, the trapped electrons have a small spin–orbit coupling and therefore small decoherence rate. In the Qd-Qc model, one electron spin per quantum dot works as a quantum qubit. Two coupled spins on two neighboring dots provide two qubit operations through the inter dot electronics exchange coupling. The external magnetic fields provide means to manipulate single qubits [4].

7. Magnetic Field Sensors

A new type of magnetic field sensor is the spin valve transistor. This transistor is based on the magneto resistance found in multilayers. The resistance of a multilayer is measured with the current in plane (CIP). The CIP configuration suffers from several drawbacks; for example, the CIP magneto resistance is diminished by shunting and diffusive surface scattering. Hence the fundamental parameters of the spin valve effect, such as the relative contribution of the interface and bulk spin dependent scattering, are difficult to obtain using the CIP geometry. Measuring with the current perpendicular to plane solves most problems, mainly because the electrons cross all magnetic layers. The spin valve transistor consists of a silicon emitter, a magnetic multilayer as the base and a silicon collector.

Electrons are injected from the emitter, passing the first Schottky barrier (semiconductor metal interface) into the base. Because of the thin base multilayer (10 nm), most electrons are not directed to the base contact and travel perpendicular through the multilayer across the second Schottky barrier to form the collector current. A Co-Cu multilayer is sputtered on one of the silicon substrates. The last layer is sputtered on both substrates and these are pressed together at the last section of the sputter deposition. A metal layer between the two crystalline semiconductors is accomplished and the bond proves stronger than silicon.

The mean free path varies with the applied magnetic field, hence the collector current becomes strongly Field dependent the extreme magneto sensitivity makes the transistors device for high technology read heads for high density Hard disks and magnetic RAM'S. 

8. Magnetic switching and microwave generation by spin transfer.

The study of the spin transfer phenomena is one of the most promising new directions in Spintronics today. In spin transfer experiments, one manipulates the magnetic moment of a ferromagnetic body without applying any magnetic field but only by transfer of spin angular momentum from a spin-polarized current. The concept, which has been introduced by John Slonczewski14 and appears also in papers of Berger15, is illustrated in Fig.4. As described in the caption of the figure, the transfer of a transverse spin current to the "free" magnetic layer F2 can be described by a torque acting on its magnetic moment. This torque can induce an irreversible switching of this magnetic moment or, in a second regime, generally in the presence of an applied field, it generates precessions of the moment in the microwave frequency range.

9. Racetrack memory

Racetrack memory uses a spin-coherent electric current to move magnetic domains along a nanoscopic perm alloy wire about 200 nm across and 100 nm thick. As current is passed through the wire, the domains pass by magnetic read/write heads positioned near the wire, which alter the domains to record patterns of bits. A racetrack memory device is made up of many such wires and read/write elements. In general operational concept, racetrack memory is similar to the earlier bubble memory of the 1960s and 1970s. Delay line memory, such as mercury delay lines of the 1940s and 1950s, are a still-earlier form of similar technology, as used in the UNIVAC and EDSAC computers. Like bubble memory, racetrack memory uses electrical currents to "push" a magnetic pattern through a substrate. Dramatic improvements in magnetic detection capabilities, based on the development of Spintronic magnetoresistive-sensing materials and devices, allow the use of much smaller magnetic domains to provide far higher bit densities [5].

Fig.-7 image for race track memory in Spintronics
Source: http://researcher.watson.ibm.com
VI. FUTURE SCOPE

1. FUTURE OF SPINTRONICS IN ELECTRONICS

A. A new combination of magnetic and semiconductor materials which are based on spin effect could lead to optical and electronic devices that are faster, smaller, reliable, economical and lower powered.

B. A number of researchers are trying to use the “spin effect” in transistors. These “Spintronic” transistors could be highly energy efficient and to do more computation than traditional transistor in smaller space.

C. In optoelectronic communication, by taking the advantage of spin of electrons lasers and light emitting diode could increases the data carrying capacity of light.

D. One of the key hurdles in the emerging field is that magnetic and semiconductor materials needed to make Spintronic device compatible, a clear interface is needed.

E. New system or Spintronic devices will maintain its magnetic properties at room temperature and some testings are needed to confirm that electrons will maintain spin characteristics while travelling from metal to semiconductor.

F. In future generation of ‘Spintronic’ devices which will be smaller in size, more versatile and more robust than those currently made from circuit elements and chips.

2. FUTURE OF SPINTRONICS IN COMPUTERS

In field of Spintronics, MRAM will soon replace conventional computer memory, domain wall storage will replace hard drives, and domain wall logic will replace the conventional computer processor [6].

The history of Moore’s law shows that many impassable barriers have subsequently been overcome by technological improvement. Limitations in engineering, manufacture and device architecture have been by-passed. The next 30 years of computing may be very different to the last 30 years.

3. INTERCONNECTS, RATHER THAN GATES ARE THE PROBLEM

Interconnects, rather than gates are the problem, the Nanoscopic cabling that connects the transistors – provide some of the greatest problems of today’s devices. For instance, it is not possible for a signal to travel across the entire processing chip within the speed of a single clock cycle (about 200ps).

Within the next 10 – 20 years replacing it will be lower-powered computers which solve more specific problems, “the most successful computers are designed for the decathlon, rather than for just the sprint only”.

4. CAN WE DELIVER ON THE HYPE?

Many ‘future technologies’ are surrounded by hype which those in the industry know can’t be delivered on. Quantum computers, carbon nanotubes and photonics all come under fire for failing to deliver on scalability, fault tolerance and their interconnects. For the Spintronics specialist there is some hope as “spin-states are particularly attractive because the promise high-density non-volatile storage”. Whether the Spintronics community can deliver on that promise remains to be seen, but this feature alone may be enough to maintain interest in the field for years to come.

For better or for worse, Spintronics research is strongly tied to technological developments and device improvements. MRAM to be the next big thing for the Spintronics industry [6].

5. THEN CAME TO THE HARD DRIVE

In memory, as opposed to storage, it is clear that semiconductors won the battle against magnets as they rose to greatness in the 1980s. In terms of long-term storage of data, however, the magnet is still king. The hard disk drive was introduced in the late 1950s and grew to become almost synonymous with computer storage itself. Over the years the hard drive has relied on a number of Spintronic phenomena to function, such as AMR and GMR. Like DRAM, however, the reign of the hard drive may have reached its zenith. Although faster and more advanced than the magnetic drum and magnetic core memories it was designed to replace, Drum memory certainly died a death, but magnetic core memory was certainly the technology of choice for the Apollo missions, several years later [6].

Ultimately semiconductors and hard drives came to dominate the world of computer memory and storage, but this paper sheds light on the hopes and aspirations of the fledgling Spintronics community at the dawn of the computer age.

VII. CONCLUSION

The new field of Spintronics was born in the intersection of magnetism, electronic transport, and optics. It has achieved commercial success in some areas and in advancing toward additional applications the rely on recent fundamental discoveries. In less than twenty years, we have seen Spintronics increasing considerably the capacity of our hard discs and getting ready to enter the RAM of our computers or the microwave emitters of our cell phones. Spintronics with semiconductor or molecules is very promising too. Some of...
the advances that might be most helpful would be room-
temperature demonstrations. Spintronics should take an
important place in the technology of our century.

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